

FRONT END OF THE RIA DRIVER LINAC

P.N. Ostroumov*, V.N. Aseev, and R.C. Pardo, Physics Division, Argonne National Laboratory, A.A. Kolomiets, ITEP, Moscow, Russia

R&D Category: Driver Front End

ABSTRACT

The RIA driver linac will deliver a wide range of ions to secondary beam targets. The linac is designed for simultaneous acceleration of ions with different charge states to obtain the required beam power, up to 400 kW, even with limited intensity of highly charged heavy ions available from present electron cyclotron resonance (ECR) ion sources. The dynamics of multiple-charge-state beams have to be designed to prevent emittance growth in all sections of the linac. It is especially important to form a high quality two-charge-state beam in the front end of the linac. The proposed design of the front end of the RIA driver linac is able to select, separate and accelerate in the radio frequency quadrupole (RFQ) the required ion species of one- or two-charge states with extremely low longitudinal emittance. The front end consists of an ECR ion source located on a high-voltage platform, low energy beam transport (LEBT), RFQ and medium energy beam transport (MEBT). The first section of the LEBT is an achromatic bending system for charge-to-mass analysis and selection. For the heaviest ions with masses above 180, the transport system is able to deliver to the entrance of the first buncher a two-charge-state beam with similar Twiss parameters for both charge states. In order to match two-charge-state ions with different mass to charge ratios, the straight section of the LEBT upstream of the RFQ will be placed on a high-voltage platform. A voltage ~ 30 kV is required in order to match velocities of ions with mass to charge ratio less than the design value and to maintain the possibility to accelerate two charge states simultaneously. Several beam matching schemes in the transitions LEBT-RFQ and RFQ-MEBT have been studied. To date we have completed design studies of the front end components and we now propose to build a prototype injector which includes an existing ECR ion source, a LEBT and one-segment of the prototype RFQ.

LEBT DESIGN

The schematic layout of the RIA driver front end systems is shown in Fig. 1. The LEBT includes two main sections: 1) an achromatic bending system for charge-to-mass analysis that can select one or two charge state heavy ion beams; 2) a straight section that forms the longitudinal emittance and matches the beam to the following RFQ. The design of the straight section which comprises a multi-harmonic buncher (MHB), velocity equalizing resonator and focusing elements has been reported in ref [1]. According to ref. [1] the lowest possible longitudinal emittance of a two charge state beam accelerated through an RFQ can be obtained using an external multi-harmonic buncher (MHB). A resonator installed immediately upstream of the RFQ entrance equalizes the average velocity of ions with different charge states.

Achromatic bending system

This section consists of two 60° bending magnets, six electrostatic quadrupole lenses and a solenoid. A possibility to correct higher-order optics distortions by using several sextupoles is being studied. A high dispersion area is formed by the first magnet where the required one- or two-charge state beam can be defined and transported to the RFQ. The baseline design of the RIA driver linac calls for a 100 kW uranium beam that requires a total of ~2 pμA in charge states 28+ and 29+. The estimated total beam current extracted from the ECR will be ~3 mA. The space charge of this multi-component ion beam effects the uranium beam parameters. To compensate the linear component of the space charge forces a solenoid magnet between the ECR and bending magnet is used. It has been found that changing solenoid position and field level provides required beam matching to the location of the horizontal slits for wide range of extracted beam currents.

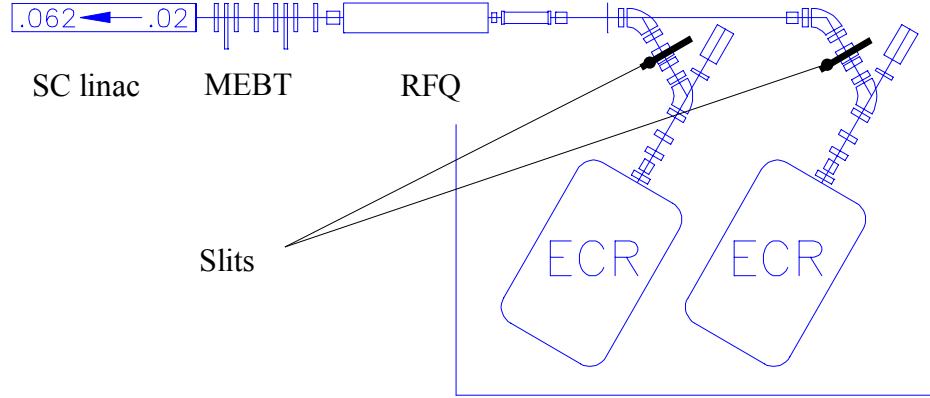


Figure 1. Front End of the RIA driver linac.

Straight section

The straight section of the LEBT includes a MHB, a velocity equalizer (VE), electrostatic quadrupoles and SC solenoid. All elements of this section except the solenoid are placed on a high voltage platform. The MHB consists of three quarter wave resonators. The first resonator provides the required voltage at the fundamental operating frequency, 28.75 MHz, and the third harmonic. The second and third resonators are operated at the second and fourth harmonics correspondingly.

The distance between MHB and VE is determined by the need to separate the two charge states into adjacent RF buckets of the RFQ and is defined by the following expression

$$L = \lambda \sqrt{\frac{2e \cdot V_0}{A m_0 c^2}} \frac{\sqrt{q_0(q_0 - 1)}}{\sqrt{q_0} - \sqrt{q - 1}}, \text{ where } e \text{ is the elementary charge, } V_0 \text{ is the accelerating}$$

voltage, A is the mass number, m_0 is the nucleon rest mass, q_0 is the highest charge state of ions, c is the speed of light, λ is the wavelength of the RFQ frequency. The distance depends on the charge-to-mass ratio and is equal to 1.507 m for the heaviest ions $^{238}\text{U}^{29+}$ and $^{238}\text{U}^{28+}$ at $V_0 = 100 \text{ kV}$.

The LEBT can be tuned to accept any two-charge-state ions with masses $A \geq 180$ by satisfying two conditions: 1) provide the design velocity at the RFQ entrance for the

average charge state; 2) provide the same time difference between the two charge states over the distance L , between the MHB and VE. The first condition is fulfilled if the voltage of the ECR ion source is $V_{01} = 2\beta_{av}^2 \frac{Am_0c^2}{e \cdot (\sqrt{q_0} + \sqrt{q_0 - 1})^2}$. The second condition can be satisfied if the MHB and VE are biased by the voltage $\Delta V = V_{01} - V_{02}$, where $V_{02} = \left(\frac{L}{\lambda}\right)^2 \frac{Am_0c^2}{2 \cdot e} \left(\frac{1}{\sqrt{q_0}} - \frac{1}{\sqrt{q_0 - 1}}\right)^2$. This value varies as a function of the charge to mass ratio of ions [2].

The electrostatic quadrupoles are used for beam focusing in this section of the LEBT and form a round beam waist both in the MHB and in the VE. Matching of the low-velocity beam to the RFQ acceptance is a challenging task due to the large difference in the focusing strength of the LEBT and RFQ. The distance between the VE and RFQ should be as short as possible in order to have effective bunching of two-charge-state beams. To minimize this space a relatively short SC solenoid in an individual cryostat is used for the matching of the axially symmetric beam to the RFQ acceptance which is defined by the RFQ radial matcher.

RFQ DESIGN

The detailed description of the RIA RFQ is given in [3]. The main goal of the beam dynamics design of the RFQ was to match the parameters of the RFQ with the longitudinal emittance formed by the MHB, eliminate halo particles from the acceleration process and keep the transverse emittance of a two-charge-state beam unchanged. To address the beam matching in the transitions LEBT-RFQ and RFQ-MEBT the entrance and exit radial matchers have been carefully designed.

Extensive studies of the driver linac RFQ has been performed during the last three years [1-6]. The following work related to the driver linac RFQ have been completed: a) beam dynamics studies and vane modulation table; b) choice of resonant structure and its electrodynamics, thermal and structural analysis; d) test of the aluminium full-scale one-segment cold model; e) development of fabrication drawings of the one-segment full-power RFQ.

BEAM DYNAMICS SIMULATIONS

The first order design of the LEBT has been carried out using TRACE-2D and -3D codes [7]. Higher order optimization has been done using the code GIOS [1,8]. The RFQ has been designed using code DESRFQ [9]. Further optimization of the LEBT has been based on simulations of multi-component heavy-ion beam dynamics using multi-particle codes TRACK [10] and DYNAMION [11]. TRACK has been especially developed for the RIA driver design and allows us to perform end-to-end simulations beginning from the ECR ion source. The main feature of the code is the use of a realistic preliminary calculated 3D representation of external accelerating and focusing fields. DYNAMION has been primarily used for the beam dynamics simulations in the RFQ.

Beam simulations start with a multi-component heavy-ion beam exiting the ECR. To

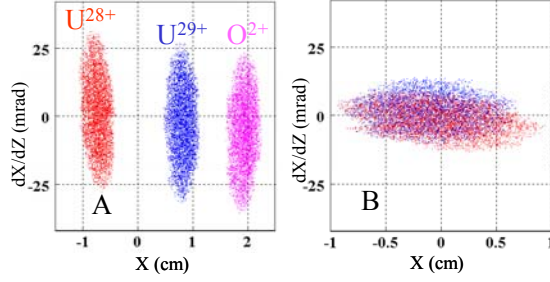


Figure 2: Transverse phase space plots in bending section. (A) at slit position shown in Fig.1. (B) – at MHB entrance.

produce 2 μA total uranium two-charge-state beam at the RFQ entrance the ECR extracts ~ 3 mA multi-component heavy-ion beam. In our design and simulation we have assumed the same Twiss parameters for all ion species exiting the ECR. Most ion species are eliminated by the first bending magnet. Fig. 2 shows phase space plots at the location of the slits shown in Fig.1. It presents the design uranium ions and nearest unwanted

ions O^{2+} simulated for a 2 mA total initial current. The simulations show the system separates charge states reliably over full range of total input beam current and provides at the MHB similar Twiss transverse parameters for both charge states. Figure 3 shows two-charge state uranium beam envelopes along the LEBT, RFQ and MEBT. Beam parameters are matched to the acceptance of the SC linac. These simulations were performed for $4 \cdot 10^4$ particles without space charge and higher-order corrections along the LEBT. Rms emittance growth in this simulations is 11%. Rms emittance in the longitudinal plane is $0.16 \pi \cdot \text{keV/u-nsec}$.

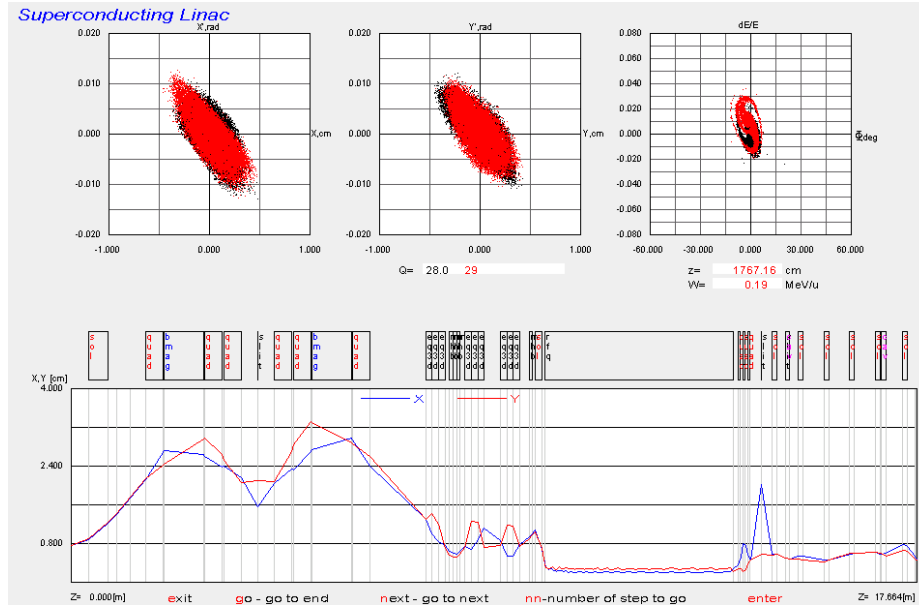


Figure 3: Two charge state uranium beam envelopes along the LEBT-RFQ-MEBT. Transverse and longitudinal phase space plots are shown at the end of the MEBT.

FUTURE WORK

- 1) Further optimisation and beam dynamics studies of the front end are needed:

- Design of the high voltage extraction electrodes using the realistic multi-component ion beam parameters from the ECR source.
- Optimisation of the LEBT including of space charge and higher order optics.
- Study of alternative options of the LEBT.
- Beam collimation, cleaning of the 4-dimensional beam emittance in the LEBT and MEBT.
- Design of the light-ion RFQ injector as an option to provide improved performance of the driver linac.

2) We plan to build a prototype of the 2q-LEBT including ECR, achromatic bends, MHB and one-segment RFQ. The main goals are to:

- Confirm two-charge-state low-emittance performance of the LEBT and RFQ.
- Test of gridless multi-harmonic buncher with fundamental frequency 28.75 MHz.
- Test of fabrication technique of the RFQ and demonstration the RFQ operation in wide dynamic range of rf power without multipacting.

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